

New Interpretation of Superhumps

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ABSTRACT

Observational evidence is presented for periodically variable irradiation of secondary components. This results in strongly modulated mass outflow. Superhumps are then due to enhanced dissipation of the kinetic energy of the stream.

Qualitative interpretation of superhump periods and their variations is also presented.

Key words: *accretion, accretion disks – binaries: cataclysmic variables, stars: dwarf novae*

1. Introduction

Superhumps are common among dwarf novae of the SU UMa subtype during their superoutbursts (Warner 1995, Hellier 2001). They are also observed in the case of the so-called permanent superhumpers (cf. Patterson 1999). The superhump periods are slightly longer than the orbital periods and their amplitudes are – typically – 0.3 mag.

The commonly accepted "tidal" model explains superhumps as being due to tidal effects in the outer parts of accretion disks leading – via the 3:1 resonance – to the formation of an eccentric outer ring undergoing apsidal motion. This model and, in particular, the results of numerous 2D and 3D SPH simulations (cf. Smith et al. 2007 and references therein) successfully reproduce the observed superhump periods and correlations of the superhump period excess with the orbital period and the mass-ratio. Moreover, those correlations find natural interpretation in the context of structure and evolution of the secondary components (Patterson 1998, 2001, Patterson et al. 2005).

On the other hand, however, the tidal model fails to reproduce the amplitudes of superhumps: The numerical SPH simulations produce "superhumps" which have amplitudes ~ 10 times too low, compared to the observed amplitudes (Smak 2009a). This implies that the nature of superhumps requires another explanation.

Recent analysis of superhumps in Z Cha (Smak 2009b) showed that – contrary to the "tidal" interpretation – they are due to strongly modulated mass transfer rate. The question then appears: what is the origin of those modulations? The answer to this question is given in the present paper.

In Section 2 we present observational evidence for variable irradiation of secondary components. Its consequences are discussed in Section 3 in terms of the irradiation modulated mass outflow. In Section 4 we discuss the relationship between the irradiation periods and the observed superhump periods and present general discussion of their variability. Results are summarized in Section 5.

2. The Missing Link

Many years ago Schoembs (1986) discovered that the luminosity of OY Car during its November 1980 superoutburst varied with period close to the beat period. Until now, however, the significance of this discovery has not been fully appreciated.

To see whether such a behavior is common among other dwarf novae a search was made through the literature for light curves well covering all beat phases. Fifteen such cases were found, including 12 dwarf novae observed during their superoutbursts and 3 permanent *positive* superhumpers. They are listed in Table 1, where the first six stars, which are eclipsing systems, are arranged in order of decreasing orbital inclinations, while the remaining, non-eclipsing systems – in alphabetical order. For eight of them it was possible to use the pure disk magnitudes measured away from eclipses and from superhumps. For the others – only nightly mean magnitudes were available.

We analyze those light curves in the following way. To begin with, using the orbital and superhump elements, we calculate the beat phases

$$\phi_b = \phi_{orb} - \phi_{sh} . \quad (1)$$

In three cases, where no orbital periods were available, their values had to be determined from their superhump periods using formula given by Menninckent et al. (1999). Consequently an arbitrary zero-point of ϕ_b had to be adopted.

Anticipating further considerations it may be worth recalling that the beat phase refers to the beat period which is defined by the other two periods as

$$\frac{1}{P_b} = \frac{1}{P_{orb}} - \frac{1}{P_{sh}} . \quad (2)$$

The observed light curves are fitted with a simple formula:

$$m = m(t_o) + \frac{dm}{dt}(t - t_o) - A \cos(\phi_b - \phi_b^{max}) , \quad (3)$$

Table 1
Photometric Data

Star	i	Data source	
IY UMa	86.8	Patterson et al. (2000a), Fig.2, JD2451562-569	2
DV UMa	84.0	Patterson et al. (2000b), Table 1 + Fig.3, 1997	3
OY Car	83.3	Schoembs (1986), Fig.1	2
Z Cha	80.2	Kuulkers et al. (1991), Table 3	3
WZ Sge	75.9	Patterson et al. (2002), Table 1, JD2452126-137	3
U Gem	69.0	Smak and Waagen (2004), JD 2446344-376	3,4
V603 Aql		Patterson et al. (1993a), Table 1	3
VY Aqr		Patterson et al. (1993b), Fig.7, JD2446558-566	2,5
TT Ari		Wu et al. (2002), Fig.1	2
TT Boo		Olech et al. (2004), Fig.3	2,5
V503 Cyg		Harvey et al. (1995), Table 3, JD2449601-609	3
VW Hyi		Schoembs and Vogt (1980), Fig.2a, JD2443808-815	2
BK Lyn		Skillman and Patterson (1993), Table 1, 1992/93	1,3
TU Mon		Stolz and Schoembs (1984), Fig.2	2
KS UMa		Olech et al. (2003), Fig.3	2,5

Remarks: 1. PG 0917+342, 2. pure disk magnitudes, 3. mean magnitudes, 4. mean points in 0.1 phase bins, 5. zero-point of ϕ_b arbitrary.

where the first two terms describe the slow brightness decline during superoutburst, while the third – the expected modulation with the beat period. The residual magnitudes are then determined as

$$\Delta m = m - \left[m(t_o) + \frac{dm}{dt}(t - t_o) \right]. \quad (4)$$

Results are listed in Table 2 and shown in Figs.1 and 2. As we can see there is an obvious dependence on the orbital inclination: (1) There are only three cases showing large variations of Δm with ϕ_b , with full amplitudes $2A \sim 0.35 - 0.40$ mag. Those are the deep eclipsers with highest orbital inclinations (OY Car, IY UMa and DV UMa). Worth noting is that they have also very similar phases of maximum. (2) The other three eclipsing systems with lower inclinations (Z Cha, WZ Sge and U Gem), show much smaller amplitudes which, in view of their large errors and large scatter of points seen in Fig.1, can hardly be considered significant. Plotted in Fig.2 is also another eclipsing dwarf nova XZ Eri, which was analyzed

earlier by Uemura et al. (2004). During one of its superoutbursts they detected low amplitude variations with a period $P = 4.7$ d, but no measurable variations with the beat period $P_b = 2.33$ d. It is plotted in Fig.2 with $A = 0$ at $i = 80.2$ as an asterisk. (3) The non-eclipsing systems, with low inclinations, do not show any significant variations.

Table 2
Results

Star	$A(\text{mag})$	ϕ_b^{max}	Star	$A(\text{mag})$	ϕ_b^{max}
IY UMa	0.18 ± 0.04	0.67 ± 0.04	VY Aqr	0.02 ± 0.05
DV UMa	0.17 ± 0.06	0.60 ± 0.06	TT Ari	0.02 ± 0.02	0.38 ± 0.12
OY Car	0.20 ± 0.07	0.65 ± 0.07	TT Boo	0.05 ± 0.03
Z Cha	0.06 ± 0.09	0.28 ± 0.25	V503 Cyg	0.02 ± 0.06	0.10 ± 0.21
WZ Sge	0.03 ± 0.03	0.49 ± 0.13	VW Hyi	0.05 ± 0.03	0.20 ± 0.20
U Gem	0.04 ± 0.04	0.35 ± 0.18	BK Lyn	0.02 ± 0.01	0.84 ± 0.17
			TU Mon	0.01 ± 0.08	0.59 ± 0.23
V603 Aql	0.02 ± 0.02	0.35 ± 0.19	KS UMa	0.02 ± 0.01

There appears to be a simple interpretation of those results. Disks in dwarf novae during their superoutbursts and in permanent superhumpers have strongly non-axisymmetric structure, rotating – in the observer’s frame – with a period P_{rot} , which is related, but only approximately equal (see Section 4), to the observed beat period P_b . In particular, the effective geometrical thickness of the disk z/r must depend on the position angle or – in the observer’s non-rotating frame – on the phase of P_{rot} . If so, the observed periodic light variations with period P_b can be interpreted as being due to variable obscuration of the central parts of the disk, resulting from variable z/r .

It is obvious that such variations can be seen only at orbital inclinations fulfilling the condition: $\cos i \approx z/r$. As can be seen from Fig.2, the three systems showing such variations have orbital inclinations corresponding to $z/r = 0.06 - 0.12$. This is, indeed, typical for hot disks with $\dot{M} = 10^{17} - 10^{18}$ g/s (cf. Smak 1992). In the case of Z Cha and XZ Eri, however, we get $z/r = 0.17$ which would require unacceptably high accretion rate $\dot{M} = 10^{19}$ g/s.

Modulations of disk luminosities with P_{rot} (in the non-rotating frame of the observer) imply variable irradiation of the secondary component (in its rotating

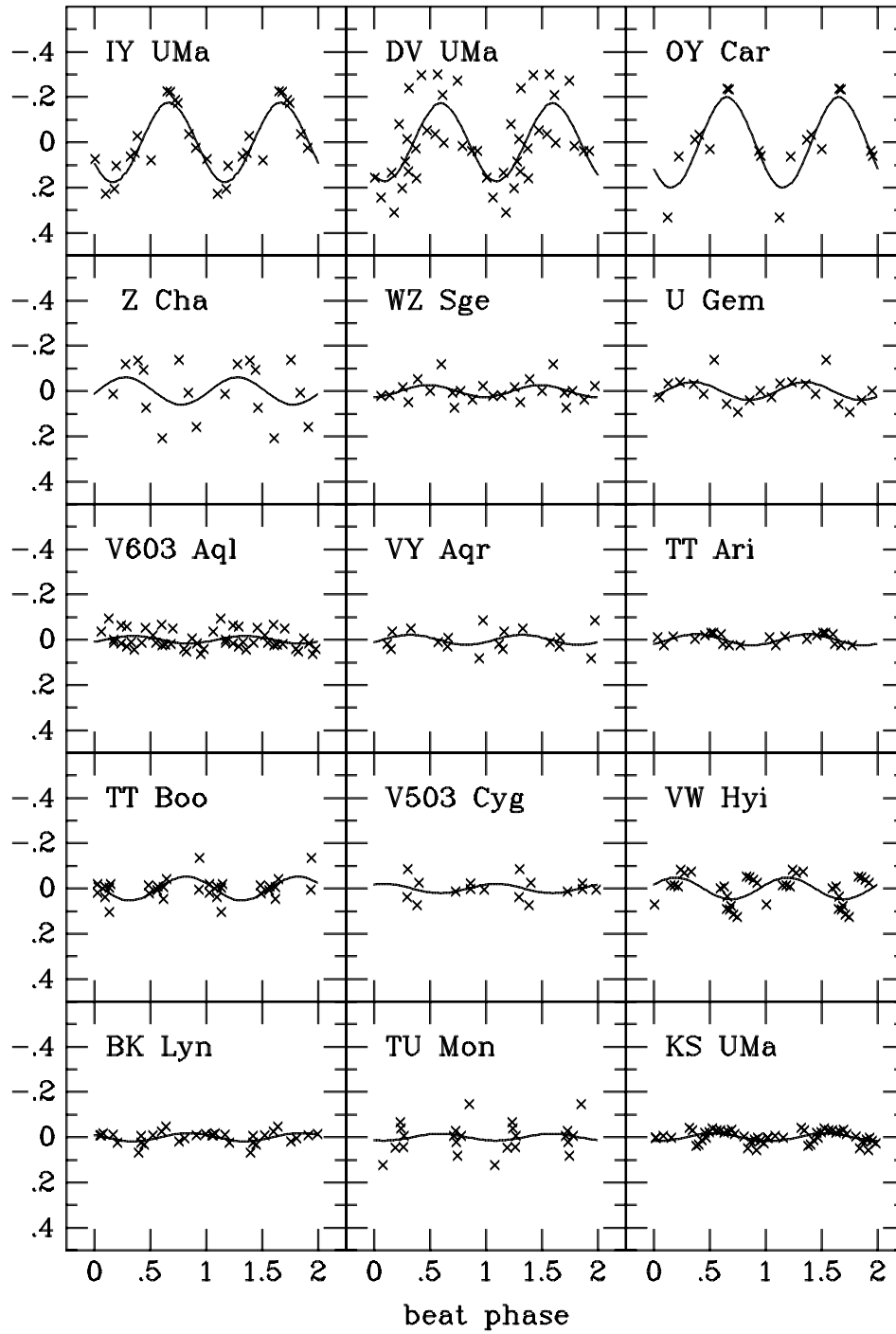


Fig. 1. Residual magnitudes versus beat phase for stars listed in Table 2. Solid lines are cosine curves with A and ϕ_b^{max} obtained from solutions with Eq.(3).

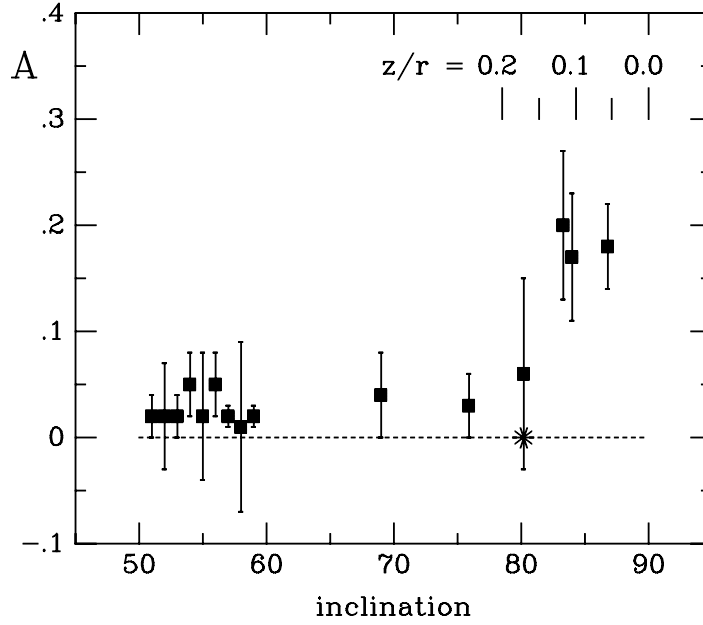


Fig. 2. The amplitude as a function of inclination for stars listed in Table 2. Non-eclipsing systems with unknown inclinations are plotted between $i = 50^\circ$ and 60° . An asterisk denotes XZ Eri. Marked above are values of $z/r = \cos i$.

frame) with "irradiation period" P_{irr} which – in analogy to Eq.(2) – is defined by

$$\frac{1}{P_{rot}} = \frac{1}{P_{orb}} - \frac{1}{P_{irr}}, \quad (5)$$

and therefore is approximately (see Section 4) equal to the observed superhump period.

3. Irradiation Modulated Mass Outflow

Irradiation of the secondary component was discussed by many authors as an important factor controlling the mass outflow from the inner Lagrangian point L_1 . The main problem here is connected with the fact that the equatorial parts of the secondary, including L_1 , are in the shadow cast by the disk and therefore are not directly affected by irradiation. Results of very crude model calculations (Smak 2004) showed that (1) the hot material flowing from irradiated regions can reach the vicinity of L_1 , and (2) its temperature at L_1 is still high enough to produce substantial enhancement in the mass outflow rate. More recent model calculations by Viallet and Hameury (2007) confirmed the first conclusion, but not the second: according to them the flow, when it reaches L_1 , is already too cool to produce any significant effects. It appears, however, that this result was mainly due to one of their assumptions. The rate of cooling of an isothermal layer is determined by its

surface effective temperature T_e which – due to that cooling – is lower than the temperature T of the layer itself. Viallet and Hameury assumed $T_e = T$ thereby overestimating the cooling effects. Further model calculations are needed.

The superhump phase of maximum irradiation of the secondary component ϕ_{sh}^{max} is related to the observed phase of maximum luminosity ϕ_b^{max} (see previous Section) by $\phi_{sh}^{max} = -\phi_b^{max}$. This means that the maximum irradiation preceeds the next superhump by

$$\Delta t = \phi_b^{max} P_{sh} = \phi_b^{max} \frac{P_{sh}}{P_{orb}} P_{orb} . \quad (6)$$

This delay consists of two terms:

$$\Delta t = \Delta t_{flow} + \Delta t_{str} , \quad (7)$$

where Δt_{flow} is the time needed for the flow to reach L_1 , and Δt_{str} is the time needed for the stream to reach the point of impact.

The last equation can be used to estimate Δt_{flow} . From IY UMa, DV UMa and OY Car, using their average values of $\langle \phi_b^{max} \rangle = 0.64$ and $\langle P_{sh}/P_{orb} \rangle = 1.028$, we get $\Delta t = 0.66 P_{orb}$. Values of Δt_{str} can be obtained from stream trajectory calculations. With $\langle q \rangle = 0.13$ we get from $\Delta t_{str} = 0.19 P_{orb}$ at the edge of the disk to $\Delta t_{str} = 0.23 P_{orb}$ at a point half way between disk edge and its center. Inserting those values into Eq.(7) we obtain: $\Delta t_{flow} = (0.43 - 0.47) P_{orb}$.

Two comments are worth to make at this point. First, that surprisingly similar values: $\Delta t_{flow} \sim 0.4 P_{orb}$ were predicted by our crude model calculations (Smak 2004, Table 2). Secondly, that – should the flow time be actually much longer – then our result would have to be rewritten in a more general form as $\Delta t_{flow} = (0.43 - 0.47) P_{orb} + n P_{orb}$.

4. The Superhump Periods and their Variations

In the previous Sections we discussed only the effects of periodic variations of z/r which occur on a short time scale corresponding to P_{sh} . Let us now consider its variations on a longer time scale. During superoutbursts the mass transfer and accretion rates change considerably resulting in significant variations of the irradiating flux and the effective geometrical thickness of the disk (averaged over all position angles). Generally we have: $F_{irr} \sim \dot{M}$ and $z/r \sim \dot{M}$ (cf. Smak 1992). Therefore: $dF_{irr}/d\dot{M} > 0$ and $d(z/r)/d\dot{M} > 0$. The flow time depends on both those factors and, in particular, we expect $\partial\Delta t_{flow}/\partial F_{irr} < 0$ and $\partial\Delta t_{flow}/\partial(z/r) > 0$. The flow time is then predicted to vary as

$$\frac{d\Delta t_{flow}}{dt} = \left[\frac{\partial\Delta t_{flow}}{\partial(z/r)} \frac{d(z/r)}{d\dot{M}} + \frac{\partial\Delta t_{flow}}{\partial F_{irr}} \frac{dF_{irr}}{d\dot{M}} \right] \frac{d\dot{M}}{dt} . \quad (8)$$

We note that the first term in the square brackets (with z/r) is positive while the second term (with F_{irr}) is negative. Therefore, depending on which of the two factors is dominant, the expression in the square brackets can be either positive or negative.

Taking into account variations of Δt_{flow} , and assuming that Δt_{str} is practically constant, we obtain the following equation connecting the observed superhump period with irradiation period (introduced in Section 2 via Eq.5)

$$P_{sh} = P_{irr} \left[1 + \frac{d\Delta t_{flow}}{dt} \right]. \quad (9)$$

As we can see, the two periods are equal only when $\Delta t_{flow} = \text{const}$ (in such a case we also have $P_b = P_{rot}$). When Δt_{flow} changes with time the two periods differ by a small amount, depending on the value and sign of $d\Delta t_{flow}/dt$.

Let us now turn to the problem of superhump period variations. Up to mid 1990-ies nearly all dwarf novae observed until that time showed superhumps with periods which were *decreasing* during superoutburst (see Warner 1995). This was interpreted (cf. Lubow 1992) as being due to decreasing disk radius. Such an effect was indeed predicted by the thermal-tidal instability model of Osaki (1989). In particular, his calculations showed that the contraction of the disk begins at the very beginning of the superoutburst and continues throughout its main part. This interpretation, however, must be abandoned for two reasons. First, there is no observational evidence for such disk radius variations. Secondly, superoutbursts are not due to thermal-tidal instability, but due to a major enhancement in the mass transfer rate (Smak 2008). As a result, the accretion is quasi-stationary, with strongly enhanced accretion rate, causing disk radius to be close to the tidal radius and remain constant throughout the entire superoutburst.

Situation became more complicated with the discovery of a group of dwarf novae with shortest orbital periods showing *increasing* superhump periods (Kato et al. 2001, 2003, Olech et al. 2003, and references therein) and even more so with the discovery of several examples of more complex *alternating* period variations (e.g. Olech et al. 2004, Rutkowski et al. 2007).

The new interpretation of superhumps emerging from considerations presented above adds another dimension to this problem. From Eq.(9) we get

$$\frac{dP_{sh}}{dt} = \frac{P_{sh}}{P_{irr}} \frac{dP_{irr}}{dt} + P_{irr} \frac{d^2\Delta t_{flow}}{dt^2}. \quad (10)$$

This equation shows that superhump periods can change due to (1) variations of P_{irr} (resulting from variations of P_{rot}), and (2) non-linear variations of Δt_{flow} (as described by its second derivative). It explains why the observed period variations can be so complex.

At the present moment we can present – mainly for illustrative purposes – only some crude, qualitative considerations. For this purpose let us arbitrarily assume

(1) that P_{irr} is constant, and (2) that the expression in the square brackets in Eq.(8) remains constant or changes with time only slightly so that the main contribution to the second derivative of Δt_{flow} in Eq.(10) comes from variations of \dot{M} . If so, Eq.(10) can be replaced with

$$\frac{dP_{sh}}{dt} \approx P_{irr} \left[\frac{\partial \Delta t_{flow}}{\partial (z/r)} \frac{d(z/r)}{d\dot{M}} + \frac{\partial \Delta t_{flow}}{\partial F_{irr}} \frac{dF_{irr}}{d\dot{M}} \right] \frac{d^2 \dot{M}}{dt^2}. \quad (11)$$

The accretion rate decreases during the main part of the superoutburst. In particular, we have $d \log \dot{M} / dt \approx \text{const}$ (cf. Fig.3 in Smak 2008) which implies $d^2 \dot{M} / dt^2 > 0$. The resulting variations of P_{sh} , however, will be either positive or negative, depending on the sign of the expression in the square brackets: When z/r is the dominant factor we predict $dP_{sh}/dt > 0$. Conversely, when F_{irr} is the dominant factor we expect $dP_{sh}/dt < 0$.

Turning to observations we recall that superhump periods of dwarf novae with longer periods are generally *decreasing*, while those of dwarf novae with shortest periods are *increasing* (Kato et al. 2003, Fig.14, Olech et al. 2003, Fig.9). The transition occurs around $P_{irr} \sim 0.06\text{d}$. Our predictions could then suggest that the dominant factor in the first case is z/r , while in the second – F_{irr} . In addition, there is a group of dwarf novae showing *alternating* variations of P_{sh} (Olech et al. 2003, 2004, Rutkowski et al. 2007). Their periods are close to P_{irr} and this could suggest that in their case z/r and F_{irr} are equally important, resulting in a more complex behavior.

Needless to say, detailed model calculations will be needed to confirm this simple interpretation and to perform the quantitative analysis of the problem.

5. Discussion: the Nature of Superhumps

Combining earlier evidence showing that superhumps in Z Cha are due to strongly modulated mass transfer rate (Smak 2009b) with evidence presented in the present paper we propose the following new interpretation of superhumps:

(1) Irradiation of secondary components is observed to vary periodically with period P_{irr} which is close (but not exactly equal) to the observed superhump period P_{sh} . The basic "clock" mechanism must then be the same as in the case of the "tidal" model.

(2) Variable irradiation of the secondary component results in mass outflow being strongly modulated with period equal to the observed superhump period.

(3) Superhumps are then due to enhanced dissipation of the kinetic energy of the stream.

Two kinds of models are now needed for a more meaningful, quantitative interpretation of superhumps and, in particular, of their variable periods:

(1) Realistic 3D disk models, including the effects of stream overflow and variable mass transfer rate. They are needed (i) to identify the nature of the "clock" and (ii) to determine z/r and F_{irr} as functions of time.

(2) Models describing the irradiation modulated mass outflow. They are needed (i) to determine Δt_{flow} and \dot{M} as functions of z/r and F_{irr} (see Section 4) and (ii) to study the relationship between P_{irr} and P_{sh} .

It can be hoped that once such models become available it will be possible to discuss not only the *common* superhumps and their periods, but also the other members of the "superhump zoo" (cf. Patterson et al. 2002).

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